LCA Case Studies

Environmental Assessment of Digestibility Improvement Factors Applied in Animal Production

Use of Ronozyme® WX CT Xylanase in Danish Pig Production

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Abstract

Background, Aims and Scope. Many feed ingredients are not fully digested by livestock. However, the addition of digestibility-improving enzymes to the feed can improve the absorption of e.g. energy and protein and thereby enhance the nutrient value of the feed. Feed production is a major source of environmental impacts in animal production, and it is obvious to assume that enzyme supplementation can help to reduce the environmental impact of animal production. The purpose of the study is, therefore, to assess and compare the environmental burdens of the supplements and compare them with the savings made when enzymes are used in animal production. The properties of enzymes vary considerably and the study takes as its starting point a particular enzyme product, Ronozyme WX CT. Ronozyme WX CT is a xylanase which depolymerises xylans (a group of dietary fibres found in cereal cell walls) into smaller units. The product is a widely accepted means of improving the energy value and the protein digestibility of pig and poultry feed. The study relates to Ronozyme WX CT used for fattening pigs produced in Denmark.

Methods. Lifecycle assessment is used as the analytical method, and Ronozyme WX CT production and reductions in feed consumption are modelled using SimaPro 7.0.2. Data on Ronozyme WX CT production are derived from Novozymes' production facilities in Denmark. Other data are derived from the literature and from public databases. Changes in feed consumption are determined by modelling in AgroSoft® feed optimisation software. Guidelines from the Intergovernmental Panel on Climate Change (IPCC) are used to estimate reductions in the emission of greenhouse gases resulting from reduced manure generation and changed manure composition.

Results. The study shows that the use of Ronozyme WX CT to increase the nutritional value of pig feed is justified by major advantages in terms of reduced potential contribution to global warming, acidification and photochemical ozone formation and reduced use of energy, and in most cases also nutrient enrichment and use of agricultural land. Ronozyme WX CT (xylanase) is often used together with Ronozyme P5000 CT (phytase) and together the two products can contribute considerably to reducing a broad range of environmental impacts from pig production.

Discussion. Reduced contribution to acidification and nutrient enrichment is partly driven by reduced feed consumption and partly reduced N-emissions with manure resulting from reduced protein content of the feed. Sensitivity analyses of a range of parameters show that the observed advantages are generally robust although exact magnitudes of environmental advantages are associated with much variation and uncertainty. It should, however, be noted that changes (e.g. of feed prices) may turn contributions to nutrient enrichment and use of agricultural land into trade-offs.

Conclusions. Improvement of energy and protein value of pig-feed by application of Ronozyme xylanase and following feed savings reduces impact on environment per unit of pig-meat produced, and the enzyme product contributes to a sustainable development the Danish pork meat supply.

Recommendations. Digestibility-improving enzymes are a promising means of reducing the environmental impact of pig production. The greenhouse gas reducing potential of Ronozyme WX CT in Danish pig production has been estimated at 5% and in the order of 4 million tons of CO_2 equivalents if the results are extended to the whole of Europe. Use of Ronozyme WX CT is driven by overall cost savings in animal production, and it is therefore recommended that digestibility-improving enzymes are given more attention as a cost-efficient means of reducing greenhouse gas emissions.

Keywords: Animal production; biotechnology; Danish pig production; digestibility; environment; enzymatic; enzyme; feed; manure; pig; Ronozyme; xylanase

Introduction

Many feed ingredients are not fully digested by livestock. However, the addition of digestibility-improving enzymes to the feed can improve the absorption of the feed components and enhance the value of the feed as a source of energy, protein and other nutrients (Schäfer et al. 2007, Ullmann's 2003). Depending on enzyme and animal type, the immediate advantages to the farmer are reduced feed expenditure and improved animal health. Previous environmental studies have, however, shown that feed production is a major source of environmental impacts in for instance pig production (Eriksson et al. 2005), and it is obvious to assume that, in addition to the immediate advantages to the farmer, there may also be a range of environmental advantages, as less nutrient supplementation is needed and less

feed is consumed per unit of animal produced. Nielsen and Wenzel (2007) have previously documented the environmental benefits of substituting a nutrient (inorganic phosphorus) in feed with an enzyme (phytase) and it could be interesting to expand the scope to other types of digestibility-improving enzymes and assess to what extent the observations apply also to the feed-saving enzymes.

The purpose of the present study was, therefore, to assess and compare the environmental burdens of the supplements that are associated with the use of a feed-saving enzyme with the savings obtained due to the better digestion.

Digestibility improving enzymes vary considerably (Schäfer et al. 2007) and the study takes as its starting point a particular enzyme, namely the enzyme product Ronozyme WX CT. Ronozyme WX CT is a an industrially produced endo-1,4-beta-xylanase which depolymerises xylans (a group of non-starch polysaccharides) into smaller units. The enzyme product has a positive effect on the feed conversion efficiency in non-ruminants (DSM 2005, Tybirk 2005) because these animals do not have the endogenous enzymes needed to degrade dietary fibre constituents such as xylans. Pigs and poultry are non-ruminants and the use of xylanase is widely accepted as a means of improving the energy and protein value of their diet. The enzyme product, which is derived from *Thermomyces lanuginosus spp*. and produced by submerged fermentation by Novozymes A/S (Denmark), and marketed by DSM Nutritional Products (Switzerland) is authorised in the EU (Commission Regulations (EC) No 1332/2004 and No 2036/2005). The focus of the current investigation is on the environmental implications of using Ronozyme WX CT in pig feed.

1 Method

Animal feed for commercial animal production must meet a range of requirements in terms of nutrient value to the animals at the lowest possible price, and is often optimised in terms of composition by computer modelling by feed producers. The study addresses changes in environmental impact when a feed producer switches from a commercial feed product without Ronozyme WX CT to a commercial feed product with Ronozyme WX CT. The composition of commercial feed products with and without Ronozyme WX CT is modelled using AgroSoft® WinOpti, a software product used in practice in animal feed optimisation. Reductions in CH_4 emissions as a consequence of reduced manure generation coming from reduced feed consumption are determined by modelling (IPCC 2006) based on the following assumptions. Dry matter content of feed: 86% (Christiansen 2005), average dry matter digestibility coefficient of the feed: 83% (Poulsen et al. 2001), maximum methane-producing capacity = 0.45 m^3 CH_4 kg^{-1} of VS excreted (Western Europe), methane conversion factor: 17% (liquid manure) and 2% (solid manure), percentage of Danish pig manure treated as liquid and solid are 92% and 8% respectively (Poulsen et al. 2001), methane density: 0.67 kg/m^3. The environmental assessment is based on principles described by Wenzel et al. (1997). Modelling has been facilitated using the LCA software SimaPro 7.0.2. A marginal and market-oriented approach is taken in the study, and co-product issues are handled by system expansion (see Wenzel 1998, Weidema et al. 1999, Ekvall and Weidema 2004). Critical assumptions and uncertain data are addressed by sensitivity analysis.

2 Scope

2.1 Functional unit (fu)

The function of Ronozyme WX CT is to break down cereal fibres and make more constituents of the feed available to the animals, so that feed composition can be adjusted and feed consumption can be reduced without compromising meat production. The functional unit of the study is, therefore, a certain (but unspecified) quantity of meat and the study provides an assessment of the changes in environmental impact and resource consumption when one switches from producing one ton of feed without Ronozyme WX CT to a nutritionally equivalent but reduced quantity of feed with an altered ingredient composition with Ronozyme WX CT added. The amount of meat produced is not quantified because it is unnecessary for the assessment and depends on a range of variable factors such as animal breed, production conditions, etc. (**Fig. 1**). The functional unit is, however, in the order of 280 kg meat (carcass weight), because about 270 kg feed is used to produce one pig of around 100 kg and about 76% of the pig is meat (Christiansen 2005).

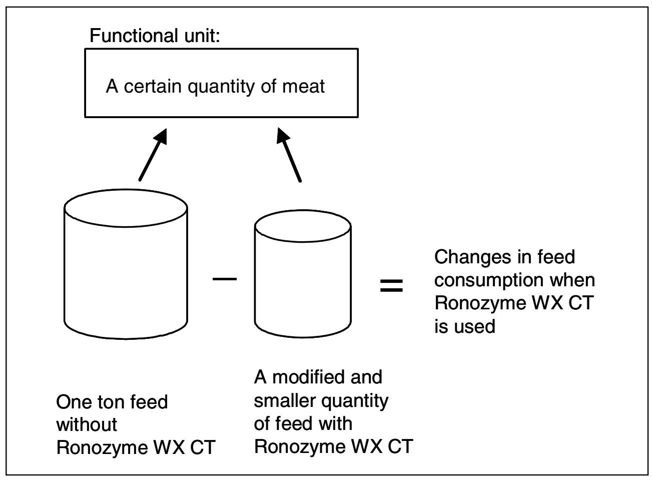

Fig. 1: Illustration of the relationship between the functional unit of the study and the changes in feed composition under consideration

2.2 Animal category, geographical scope and time perspective

The study addresses fattening pigs (25–100 kg) produced in modern production systems in Denmark. Ronozyme WX CT can be added to or removed from the feed without capital investment, and introduction of the product in the feed has no long-term implications.

2.3 Indicators

The main environmental issues in the system under consideration are deemed to be potential contributions to global warming, acidification, nutrient enrichment and photochemical ozone formation and the essential resource consumptions

are considered to be energy use and use of agricultural land, and indicators are included accordingly. Characterisation is based on Eco-indicator 95 v. 2.03. Normalisation refers to Denmark (Stranddorf et al. 2005).

2.4 System boundaries

The main system boundaries of the study are shown in **Fig. 2.** The figure illustrates that the use of Ronozyme WX CT increases barley consumption and reduces soy, wheat and animal fat consumption. The changes in feed composition and the reduced feed consumption lead to reduced manure generation per unit of meat produced and reduced N content of the manure. N in manure serves as a fertiliser in crop production, and reduced N content increases the need for alternative N-fertiliser to maintain crop production. Artificial fertiliser production is regulated by fertiliser demand (in contrast to manure, which is determined by animal product demand) and artificial N-fertiliser meets the need. Emissions of N_2O and NH_3 from the stable and from manure storage systems decrease when the N content of the manure decreases. Similarly, emissions of N_2O, NH_3 and NO_3 from the agricultural land receiving the manure decrease because N emissions from manure are greater than emissions from artificial N-fertiliser. Carbon contained in the manure is to some extent converted into CH_4 during storage in the stable and in manure storage systems, and reduced manure generation per produced unit of meat results in reduced CH_4 emissions. The details are given in the following sections.

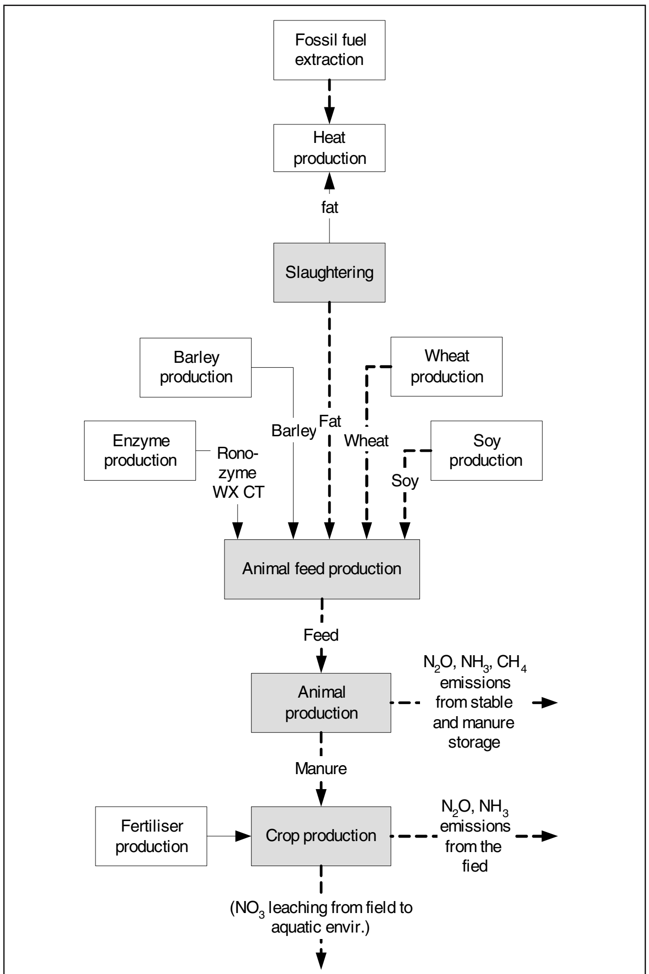

Fig. 2: Main system boundaries of the study of Ronozyme WX CT used in pig production. Full arrows indicate increased material streams, while dotted arrows indicate reduced material streams. Processes indicated with white boxes are influenced by Ronozyme WX CT application and included in the study. Grey boxes indicate processes which are independent and hence not included in the study. Reductions in emissions of N_2O, NH_3 and CH_4 to the atmosphere from stable/manure storage and field due to changed and reduced feed consumption are included in the study. Reductions in the leaching of NO_3 (in brackets) are not

All environmentally significant processes are included in the study, except reductions in NO_3 emissions to the aquatic environment due to the reduced N content of the manure. The reason is that the available data basis and modelling tools for estimating the reduction in NO_3 emissions from farmland are considered too uncertain to be included in the base case of the study. The significance of neglecting NO_3 emissions in the study has, however, been addressed in sensitivity analyses, based on the best available models.

3 Data Basis and Modelling

3.1 Production of Ronozyme WX CT

Ronozyme WX CT is a granulated enzyme product produced in Novozymes' factories in Denmark. The assessment of the product includes all heat, electricity and water consumptions in production and waste management and 99% (w/w) of ingredients. Modelling is based on 2005 recipes. Modelling follows Nielsen et al. (2007) except that the marginal source of electricity has been switched from natural gas to coal (Behnke 2006).

3.2 Modification of feed and reduction of feed consumption

Pig feed can be composed in many different ways and the implications of Ronozyme WX CT application can be numerous. The study addresses economically optimised animal feed in a reference situation with no Ronozyme WX CT application and in an altered situation where Ronozyme WX CT is applied, based on feed prices in 2006 (**Table 1**).

Changes induced by the adjustment of feed composition in Table 1 are determined by subtracting the quantities of individual ingredients used to produce one ton of feed in the scenario with Ronozyme WX CT application from similar ingredients in the reference situation without Ronozyme WX CT application. Increased energy and protein values of the feed lead to a reduction in soy meal and animal fat requirements on the one hand and an increase in the use of barley on the other.

Changes induced by reduced feed consumption: The National Committee for Pig Production (Tybirk 2005) proposes a 3% feed saving when commercial xylanase products are added to pig feed. The effects of xylanase application vary with diet, animal gender, growth stage of animals, etc., and it has been assumed, conservatively, in the study that the use of Ronozyme WX CT reduces the feed demand by only 2.5%. The changes induced by reduced feed consumption influence all ingredients equally and feed savings are determined accordingly.

Table 1: Pig feed composition with and without Ronozyme WX CT application and changes induced by adjustment of feed composition and 2.5% reduced feed consumption

Feed ingredients	Without Ronozyme WX CT	With Ronozyme WX CT	Changes induced by adjustment of feed composition	Changes induced by 2.5% reduced feed consumption	Total change	Inc. in model
	$kg \cdot ton\ feed^{-1}$	$kg \cdot ton\ feed^{-1}$	$kg \cdot fu^{-1}$	$kg \cdot fu^{-1}$	$kg \cdot fu^{-1}$	
Barley	324	375	51	–9.4	42	Yes
Wheat	350	350	0	–8.8	–8.8	Yes
Wheat bran	50	50	0	–1.3	–1.3	No
Peas	30	30	0	-0.75	–0.75	Yes
Soy bean meal	182	151	–31	–3.8	–35	Yes
Animal fat	26	5	–21	–0.13	–22	Yes
Molasses	10	10	0	–0.25	–0.25	No
Ronozyme WX CT	0	0.20	0.20	–0.0050	0.20	Yes
Others	28	29	~ 0	–	-	No
Total	1,000	1,000	0	25	-	-

The total changes are determined by adding the changes resulting from adjustment of feed composition and the changes resulting from reduced feed consumption.

3.3 Modelling of feed ingredients

Data on barley, wheat and peas are from LCA food (2003), and are based on representative data for the Danish agricultural sector (Dalgaard et al. 2006). Data on barley refer to spring barley. Data on soybean meal refer to soybean production in Argentina (LCA food 2003). It is assumed that palm oil is the marginal type of vegetable oil (Schmidt and Weidema 2007) and that a marginal reduction of soy oil production resulting from a reduced soy bean meal demand leads to increased palm oil production. Data on palm oil production are derived from Ecoinvent (2005).

Animal fat from slaughterhouses is in excess in the Danish market and marginal fat is used in energy production (Hvid et al. 2005). A marginal reduction in animal fat consumption for pig production resulting from the use of Ronozyme WX CT is, therefore, likely to displace other energy sources (see Fig. 2). It is assumed that animal fat displaces an equivalent quantity of fuel oil (w/w), that the heat value of fat and fuel oil are similar and that emissions are the same. The only difference taken into account is thus that CO_2 from fuel oil is fossil and contributes to global warming, whereas CO_2 from animal fat does not because it comes from a non-fossil source.

Wheat bran is a relatively cheap feed ingredient and it is economically attractive to increase the use thereof when Ronozyme WX CT is applied because the xylanase increases the digestible protein and energy value of the product. Marginal wheat bran is, however, already used in animal feed production (Cerealia 2005) and since production is inherently determined by wheat grain production it is judged that production will remain unchanged independently of an increased demand induced by Ronozyme WX CT application. Wheat bran use has therefore been fixed at the reference level during modelling of feed composition. The result is an increase in barley consumption instead. Similar market constraints are assumed for molasses production (a co-product from sugar production) and similar modelling restrictions are applied for this ingredient.

The group of 'others' refers to a variety of vitamins and minerals which are virtually independent of Ronozyme WX CT application and hence disregarded in the assessment.

3.4 Estimation of changes in emissions from the stable and the manure storage

Evaporative emissions of N_2O, NH_3 and CH_4 are regarded as the essential emissions from stable and manure storage in Denmark where washout to the aquatic environment to a large extent is controlled. N_2O and NH_3 emissions are functions of N excretions with pig manure which is in turn a function of feed composition and feed consumption per unit of meat produced. Reductions in N excretions as a consequence of Ronozyme WX CT application is to a large extent driven by changes in feed consumption and a to lesser extent feed savings and has been estimated at 1.98 kg N per functional unit as specified in **Table 2.** The change in the N content of manure is proportional to the change in the pro-

Table 2: Estimation of changes in the protein content of feed, N content of manure and emissions of N_2O and NH_3 from stable and manure storage systems. The protein content of the feed is determined by modelling in AgroSoft. All data are provided per functional unit

Protein in feed (kg)			Change of N cont. of manure [b] (kg)	Change of emissions to air (g)	
Without Ronozyme WX CT	With Ronozyme WX CT	Change		N_2O-N	NH_3-N
165.9	153.5 [a]	–12.4	–1.98	–4.6	–400

[a] inc. 2.5% feed saving

[b] N content in protein ~ 16% (Sawyer et al. 1994)

Table 3: Estimation of changes in manure production and CH_4 emissions from stable and manure storage systems. All data are provided per functional unit

Total feed consumption (kg)			Change in manure production (kg dry matter)	Change in CH_4 emission (g)
Without Ronozyme WX CT	With Ronozyme WX CT	Change		
1,000	975	–25	–3.7	–180

Table 4: Estimation of changes in direct N_2O and NH_3 emissions from the field, when manure is replaced by artificial fertiliser

Emission and source	Fraction of N emitted	Change $g{\cdot}fu^{-1}$	Total change $g{\cdot}fu^{-1}$
N_2O-N from manure	0.01	–16	–4
N_2O-N from artificial fertiliser		+12	
NH_3-N from manure	0.02	–32	–8
NH_3-N from artificial fertiliser		+24	

tein content of the feed because meat production and hence N retention in the pig is fixed (see Fig. 1). N undergoes a range of processes in the stable and manure storage systems. The fraction of excreted N which is emitted as N_2O from stable and manure storage systems is estimated at 0.23% (Dalgaard et al. 2006, IPCC 2006) and the percentage which is emitted as NH_3 is estimated at 20% (Andersen et al. 1999).

CH_4 emission is a function of manure production which is in turn a function of feed consumption per unit of pig meat produced. It is assumed that a 2.5% feed saving (see Table 1) leads to a 2.5% reduction in manure generation, and changes in methane emission per functional unit are determined by modelling (IPCC 2006) as specified in Section 1. The results are shown in **Table 3**. Enteric methane formation in pigs is low compared with methane formation from manure (IPCC 2006) and changes in enteric methane formation are ignored in the study.

3.5 Estimation of compensatory artificial fertiliser application

Manure is used as fertiliser in crop production and reduced input of N with manure to agricultural land as a result of Ronozyme WX CT application leads to an increased demand for artificial fertiliser to maintain crop yields. It is assumed that 75% of N in manure is utilised by the crops (Danish Plant Directorate 2006) and compensatory artificial fertiliser has been estimated at 75% of the remaining N content of the manure after evaporation in stable and manure storage (see Table 2), i.e. a change of 1.2 kg $N{\cdot}fu^{-1}$. Calcium ammonium nitrate (Patyk and Reinhardt 1997) is used to represent the additional artificial fertiliser.

3.6 Estimation of changes in N_2O and NH_3 emissions from the field

The substitution of manure with artificial fertiliser leads to changes in direct N_2O and NH_3 emissions from the field. The total change in N lost by evaporation from stable and manure storage is around 400 $g{\cdot}fu^{-1}$ (see Table 2) and the remaining N content in manure has been estimated at 1.6 kg fu^{-1}. The estimation of changes in N_2O and NH_3 emissions is based on emission factors from IPCC (2006) and Andersen et al. (1999) respectively. Results are shown in **Table 4**.

3.7 Other effects of Ronozyme WX CT application

The use of xylanase has a range of positive effects on the health and growth of animals (Schäfer et al. 2007). These effects are ignored in the study because they are difficult to quantify in the present context. Better health and faster growth of animals reduces the impact of pig production per unit of meat produced, and it is considered likely that this simplification leads to a slight underestimation of the environmental advantages of Ronozyme WX CT application.

3.8 Transport

All feed ingredients except soybean meal are assumed to be produced locally and transportation is ignored because it is considered negligible. Soybean meal is assumed to be produced in South America and a rough estimate of transportation is included in the assessment (ocean freighter; 10,000 km). Ronozyme WX CT is transported from factory to feed mill via a network of supply stations and a conservative estimate of transportation is included in the assessment (lorry; 1,400 km).

3.9 Data quality assessment

Modelling of **enzyme** production is based on very detailed production information. Modelling of upstream processes is based partly on data from specific suppliers and partly on generic sources. The most important data are considered to be up to date and representative and the quality of the assessment of enzyme products is considered good.

Modelling of **feed ingredients** is to a large extent based on detailed studies of agricultural production in Denmark and the data refer to marginal suppliers in Denmark. Data are reasonably up to date and quality is generally considered good although some emissions, particularly to air and water, are associated with much variation and uncertainty.

4 Results

Changes in environmental impacts and resource consumptions when Ronozyme WX CT is used in pig feed and the composition of the feed is changed and feed consumption is reduced are shown in **Fig. 3**.

Fig. 3 shows that the impacts induced by Ronozyme WX CT production are low compared with the reduction in impacts obtained by feed savings and change of the feed composition and that considerable environmental improvements can be achieved in terms of all considered impact categories when Ronozyme WX CT is used to increase the energy and protein value of the feed.

The reduced contribution to global warming is to a large extent driven by the reduced use of soybean meal (reduced N_2O emissions from soy fields), but reductions in wheat, fat and emissions of N_2O and CH_4 from stable, manure storage and field also play a role. The increased use of barley (see Table 1) and to a lesser extent the use of fertiliser to compensate for missing N in animal manure counteract the reduced contribution to global warming, but the reduction in impact due to savings of fat, wheat and soybean meal is greater than the increase in impact due to greater barley and fertiliser consumption.

Reduced fossil energy consumption is primarily driven by the reduced use of fat in the feed (see Fig. 1) and the reduced contribution to photochemical ozone formation is primarily driven by a combination of the reductions in soy and animal fat use.

The reduced contribution to acidification and nutrient enrichment is largely driven by reduced emissions of NH_3 from the stable and manure storage (see Table 2). Contributions to acidification from increased barley and fertiliser use are small compared with the fall in contributions due to reduced NH_3 emissions. Contribution to nutrient enrichment from barley is considerable, and adjustment of the feed leads to a slight increase in impact in terms of nutrient enrichment. However, the increase is too small to outweigh the savings from saved feed, and the net result is a slight reduction in contribution to nutrient enrichment.

Reduced use of agricultural land is primarily (85%) driven by reductions in feed consumption, whereas adjustment of the feed drives the largest reductions in contributions to global warming (80%), acidification (90%), photochemical smog formation (65%), and fossil energy use (95%).

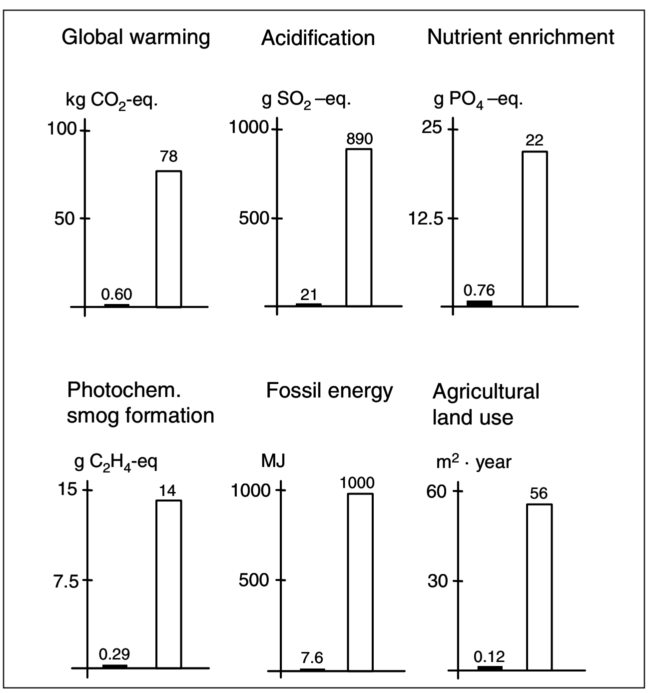

Fig. 3: Increased environmental impact potentials resulting from Ronozyme WX CT production (black bars) compared with reduced environmental impact potentials resulting from changed and reduced feed consumption (white bars). All changes are given per functional unit. Fossil energy refers to primary energy resources (lower heat value)

5 Sensitivity Analyses

A number of assumptions and simplifications have been made during the study. Some of most the important are subject to sensitivity analyses in the following in order to assess the robustness of the results.

Increased feed yield: It has been estimated conservatively that the feed saving obtained by the use of Ronozyme WX CT is 2.5%. The National Committee for Pig Production proposes a 3% feed saving (Tybirk 2005), but it is possible that the saving could be even higher. The full assessment has therefore been made with feed savings of 3.0, 3.5 and 4.5%. The results show that the estimated environmental benefits of enzyme application increase linearly when the feed saving increases. Feed saving has a considerable effect on the avoided contributions to nutrient enrichment and agricultural land use, whereas the effect on other impact categories is more limited.

Estimates of emissions from agricultural land used in crop production are uncertain and play an important role in the study. A sensitivity assessment in which emissions of the most important components (N_2O, NH_3, N_2O, NO_3, and PO_4,) from the most important fields (soy, barley and wheat fields) are varied individually and together has therefore been carried out. Uncertainty is estimated at ±20% for NH_3 and NO_3 and ±35% for PO_4 and N_2O based on Kristensen (2004) and Halberg et al. (2007). The outcome shows that the variation in NH_3, NO_3, PO_4 and N_2O emissions from the agricultural land lead to linear changes in environmental impacts and demonstrates that environmental Ronozyme WX CT is clearly advantageous in terms of all considered impact categories except nutrient enrichment independently of variations in field emissions. In most cases, Ronozyme WX CT application is also advantageous in terms of nutrient enrichment but a few cases demonstrate that it is possible that nutrient enrichment could be a trade-off if emissions from the barley field have been underestimated.

It has been assumed that palm oil is the marginal source of vegetable oil. It can, however, not be ruled out that other oils, most likely rapeseed oil, will become the marginal vegetable oil in the future and the assessment has been carried out with rapeseed oil as the marginal vegetable oil. Rapeseed production contributes more to the considered impacts than palm oil and the impact reduction obtained by Ronozyme WX CT application is therefore also smaller.

Nutrient enrichment turns out to be a trade-off of Ronozyme WX CT application whereas it remains a clear advantage for all other impact categories.

Ronozyme WX CT application increases barley consumption (see Table 1) and the environmental assessment referred to spring barley (Section 3.3). Barley is, however, also available as winter barley and the assessment has also been carried out with winter barley, since there is no indication that the one type of barley is more appropriate than the other. Except with regard to nutrient enrichment, winter barley contributes less to the environmental impacts and resource consumption under consideration than spring barley, and the switch from spring barley to winter barley emphasises the advantages of Ronozyme WX CT application slightly in terms of all impact categories except nutrient enrichment. Ronozyme WX CT application turns into a slight disadvantage in terms of nutrient enrichment.

Determination of feed composition with and without Ronozyme WX CT application is based on current feed prices. Feed prices are, however, subject to fluctuations and a series of assessments have therefore been carried out with realistic (+/–20%) variation of the relative prices of the three most important feed ingredients (barley, wheat and soybean meal). The results show that feed ingredient prices have a considerable influence on the feed composition with and without Ronozyme WX CT and hence the impact of Ronozyme WX CT application. Ronozyme WX CT application remains, however, a clear advantage in terms of all considered impact categories except nutrient enrichment and agricultural land use in a few scenarios. The reason is that the advantages of feed savings in some cases are exceeded by disadvantages from switching to crops with larger contributions to nutrient enrichment and smaller yield per area of agricultural land used. Agricultural land is currently used to produce energy crops with a CO_2 avoidance efficiency in the order of 2 to 4 tons of $CO_2 \cdot ha^{-1}$ (WTW 2006). The worst case of increased agricultural land use as a result of Ronozyme WX CT application has a greenhouse gas avoidance efficiency of 8 tons of CO_2-eq$\cdot ha^{-1}$. The agricultural land use induced by Ronozyme WX CT application is, thus considered environmentally efficient in any case. Reduced contribution to global warming varies between 30 and 80 kg CO_2 eq.$\cdot fu^{-1}$ and the average of all observations (incl. the base case, see Fig. 3) is 53 kg CO_2 eq.$\cdot fu^{-1}$.

Emissions from stables, manure storage systems and fields are dependent on a range of factors in pig production and estimates are subject to much variation and uncertainty. Sensitivity analyses where the reduction in emissions has gradually been reduced to zero show that contributions to global warming and photochemical smog formation are rather insensitive to variations (Ronozyme WX CT application is a clear advantage in terms of contribution to global warming and photochemical smog formation independently of avoided emissions), whereas contributions to acidification and particularly nutrient enrichment are very sensitive. It is estimated that NH_3 emissions (the main source of avoided contributions to acidification and nutrient enrichment) can be reduced by 50% with optimised practice (Sommer et al. 2006) and a test with 10% NH_3 emissions (instead of 20%, see Section 3.4) has been performed. The results show that Ronozyme WX CT application remains a clear advantage in terms of acidification whereas nutrient enrichment turns into a small trade-off.

Reductions in NO_3 emissions from the field have not been included in the assessment (see Fig. 1) because the data and the modelling basis were considered too poor. NO_3 contributes to nutrient enrichment and ignoring NO_3 emissions in the assessment may have lead to an underestimation of the advantages of the use of Ronozyme WX CT in terms of this impact category. Based on Dalgaard et al. (2006) rough estimates of the reduction in NO_3 (in both sandy and sandy loam soil) has been established and the assessment including the reduction in NO_3 emissions has been performed. Although the results are uncertain, they indicate that the reduction in contributions to nutrient enrichment as a result of Ronozyme WX CT application is underestimated considerably in the base case as well as in the above-mentioned sensitivity assessments, and that Ronozyme WX CT application is advantageous also in terms of nutrient enrichment in all cases except where the marginal vegetable oil switches from palm oil to for instance rapeseed oil. If the marginal vegetable oil switches to rapeseed oil, the normalised trade-off of nutrient enrichment appear to be at the same level as normalised advantages in terms of e.g. global warming.

6 Discussion

The present study has addressed Ronozyme WX CT application for pigs produced in Denmark, and the results are directly comparable with results on Ronozyme P5000 CT (phytase) application (Nielsen and Wenzel, 2007). The two enzyme products are often used together and their environmental advantages at realistic usage levels (150 g Ronozyme P5000 CT ton feed^{-1} and 200 g Ronozyme WX CT ton feed^{-1}) have been compared. The results show that the two product supplement each other in terms of environmental improvement: the xylanase's main environmental improvement potential rests in reducing contributions to global warming, acidification and photochemical smog formation and the phytase's main potential rests in reducing contributions to nutrient enrichment. Acknowledging that xylanase reduces N emissions and phytase reduces P emissions, any nutrient-enrichment-trade-offs induced by xylanase application are exceeded by much larger nutrient-enrichment-reductions obtained by phytase application when the two products are used together.

7 Conclusions

The present study shows that application of Ronozyme WX CT xylanase as a means of increasing the nutritional value of pig feed is justified by major benefits in terms of reduced contributions to global warming, acidification and photochemical ozone formation and reduced use of energy and, in most cases, also nutrient enrichment and use of agricultural land. Sensitivity analyses indicate that Ronozyme WX CT application in certain cases may lead to increased nutrient enrichment or increased use of agricultural land because the enzyme induces a switch to crops with higher impacts in terms of the two impact categories. Normalised trade-offs in terms of nutrient enrichment are the same order of magnitude as reductions in contributions to global warming and application of Ronozyme WX CT is justified unless the

weighting given to nutrient enrichment is higher than or equal to global warming. Ronozyme WX CT (xylanase) is often used together with Ronozyme P5000 CT (phytase). The phytase product has major potential for nutrient enrichment reduction and any trade-offs in terms of nutrient enrichment from xylanase application are by far exceeded by the savings obtained by phytase application. Considerable reductions of greenhouse gas emissions obtained by Ronozyme WX CT application justifies the additional agricultural land use observed in a few cases.

8 Perspectives

The use of Ronozyme WX CT saves on average 52 kg CO_2 equivalents per functional unit (53–0.60 kg CO_2 eq.·fu^{-1}, Section 5 and Fig. 3), i.e. around 185 g CO_2-eq.·kg meat^{-1} (carcass weight ex farm), see Section 2.1. The total greenhouse gas emissions from pig production are in the order of 3.5 kg CO_2-eq.·kg meat^{-1} (carcass weight ex farm; Dalgaard et al. 2007), and the study indicates that the use of Ronozyme WX CT has the potential to reduce the contribution to greenhouse effect from Danish pig production by around 5% (up to 8% and down to 3% depending on feed prices).

Sensitivity analyses have shown that avoided contribution to global warming has a limited sensitivity to parameter variation (except feed prices), and the total potential for reduction of greenhouse gas emissions from European pig production has been roughly estimated at 4 million tons CO_2-eq. if Ronozyme WX CT were implemented in all feed (assuming (i) that the effect of xylanase use on other pig groups (sows, weaners, etc.) is the same as for fattening pigs, (ii) that 270 kg feed is consumed per pig (Christiansen (2005), (iii) that 286 million pigs are produced annually in Europe (FAOSTAT 2007), and (iv) that 52 kg CO_2 eq. is avoided per ton of feed on average (see Fig. 1 and above). Xylanases (of any brand) have currently penetrated about 30% of the feed market in Europe, and a considerable environmental improvement potential is within reach. The use of Ronozyme WX CT is driven by overall cost savings in animal production, and it is therefore recommended that digestibility-improving enzymes should be given more attention as cost-efficient means of reducing greenhouse gas emissions.

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